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14. ABSTRACT

The near-threshold fatigue crack growth behavior of a 7075-T651 aluminum alloy was studied in laboratory air, vacuum, and an aqueous 3.5% NaCl solution. Results obtained indicate that raising the stress ratio R enhanced the near-threshold fatigue crack growth with a greater crack growth rate da/dN and smaller threshold stress intensity range ΔK_{th} in laboratory air and an aqueous 3.5% NaCl solution. However, the reverse was observed in vacuum. The near-threshold fatigue crack growth was most sluggish with the smallest da/dN and greatest ΔK_{th} values in vacuum, intermediate with an intermediate da/dN and ΔK_{th} in the aqueous 3.5% NaCl solution, and fastest with the greatest da/dN and smallest ΔK_{th} values in laboratory air. In laboratory air and aqueous 3.5% NaCl solution ΔK_{th} initially decreased with increasing R until a value of 0.5 was reached, and then leveled off or decreased slightly. The ΔK_{th} values for these two environments appear to converge at a higher R. On the other hand, in vacuum, the ΔKth increased linearly with increasing R. In addition, at lower R, a greater resistance to near-threshold fatigue crack growth was detected in the aqueous 3.5% NaCl solution than in laboratory air. This is attributable to crack closure, induced by corrosion product at the crack tip.

15. SUBJECT TERMS

fatigue, near-threshold fatigue crack growth, stress ratio, vacuum, laboratory air, 3.5% NaCl solution, threshold stress intensity range, maximum stress intensity

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Environmentally Influenced Near-Threshold Fatigue Crack Growth in 7075-T651 Aluminum Alloy

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Abstract: The near-threshold fatigue crack growth behavior of a 7075-T651 aluminum alloy was studied in laboratory air, vacuum, and an aqueous 3.5% NaCl solution. Results obtained indicate that raising the stress ratio R enhanced the near-threshold fatigue crack growth with a greater crack growth rate da/dN and smaller threshold stress intensity range ΔK_{th} in laboratory air and an aqueous 3.5% NaCl solution. However, the reverse was observed in vacuum. The near-threshold fatigue crack growth was most sluggish with the smallest da/dN and greatest ΔK_{th} values in vacuum, intermediate with an intermediate da/dN and ΔK_{th} in the aqueous 3.5% NaCl solution, and fastest with the greatest da/dN and smallest ΔK_{th} values in laboratory air. In laboratory air and aqueous 3.5% NaCl solution ΔK_{th} initially decreased with increasing R until a value of 0.5 was reached, and then leveled off or decreased slightly. The ΔK_{th} values for these two environments appear to converge at a higher R. On the other hand, in vacuum, the ΔK_{th} increased linearly with increasing R. In addition, at lower R, a greater resistance to near-threshold fatigue crack growth was detected in the aqueous 3.5% NaCl solution than in laboratory air. This is attributable to crack closure, induced by corrosion product at the crack tip.

Keywords: fatigue, near-threshold fatigue crack growth, stress ratio, vacuum, laboratory air, 3.5% NaCl solution, threshold stress intensity range, maximum stress intensity

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The 7075 aluminum alloy contains zinc, magnesium, copper, and chromium, and can heat-treated to a high strength in the T6 temper. In the annealed and solution-treated condition it has good formability at ambient temperatures, and in the T6 condition it has good formability at elevated temperatures. Consequently, this alloy was initially used in airframe structures, mobile equipment, and other highly stressed components. However, the T6 temper has low fracture toughness at room and cryogenic temperatures, and exhibits poor resistance to stress corrosion cracking. Eventually the T6 temper was replaced by the T73 temper, for its improved fracture toughness and stress corrosion resistance although it has a lower tensile and yield strengths.

On account of its high strength, the 7075-T6 aluminum alloy was widely used in the fabrication of airframe structures prior to the introduction of the T73 temper. Recently, a great emphasis is being placed upon the integrity and maintenance of 7075-T6 aluminum alloy structures to extend the life of aging aircraft. During their long service, many aircraft structures have been subjected to repeated loading in corrosive environments. As a result, it is highly likely that mechanical fatigue and/or corrosion fatigue has been developed in those aging structures. Therefore, it is essential to understand the fatigue behavior for assessing and extending the service life of aging airframe structures of 7075-T6 aluminum alloy. This study was initiated to characterize and understand the fatigue behavior of a 7075-T651aluminum alloy, in particular the near-threshold fatigue crack growth, in inert and corrosive environments.

Experimental Procedure

The specimen material was a 7075-T651 aluminum alloy plate with the following dimensions: 279 x 406 x 9.5 mm (11 x 16 x 3/8 in.). The nominal chemical composition and mechanical properties of the 7075-T651 aluminum alloy are shown in Tables 1 and 2, respectively. Its microstructure is also depicted in Fig. 1.

Table 1 - *Chemical Composition of 7075 Aluminum Alloy*

	Weight Percent	
Element	Min	Max
Cu	1.2	2.0
Mg	2.1	2.9
Mn	---	0.3
Fe	---	0.7
Si	---	0.5
Zn	5.1	6.1
Cr	0.18	0.4
Ti	---	0.2
Other Impurities		
Each	---	0.05
Total	---	0.15

Al	Balance

Table 2 – *Mechanical Properties of 7075-T651 Aluminum Alloy*

	MPa	ksi	%	MPa√m	ksi√in
Tensile Strength	572	83			
Yield Strength	503	73			
Elongation			11		
Fracture Toughness:					
L-T Orientation				28.6	26
T-L Orientation				24.2	22
S-L Orientation				17.6	16

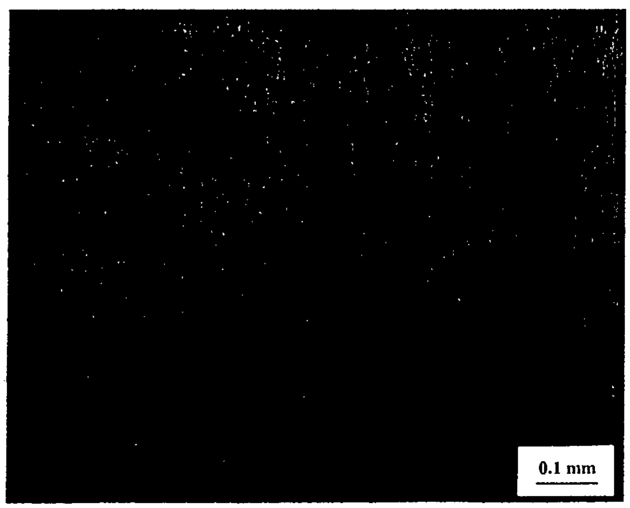


FIG. 1 - *Micrograph of specimen material reveals a microstructure of an Aluminum Alloy 7075-T651.*

Compact tension, C(T), specimens, 9.5 mm (3/8 in.) thick and 38.1 mm (1.5 in.) wide, were prepared in the L-T orientation from the plate of 7075-T651 aluminum alloy.

For the fatigue tests, two closed-loop servo-hydraulic mechanical test machines were employed. One was a 100 kN (22 kip) vertical MTS machine with a vacuum chamber for fatigue testing in vacuum or gaseous environment. The other was a horizontal mechanical test machine for fatigue testing in a liquid environment. The horizontal tester consisted of a 44.5 kN (10 kip) actuator, a 22.25 kN (5 kip) load cell, a supporting frame, and a liquid container. The liquid was constantly circulated between the container and a

3.8 liters (1 gallon) reservoir by a pump. Each test machine was interfaced with a computer system for automated monitoring of fatigue load and crack growth.

Fatigue tests were conducted under load control in tension-tension cycling with a sinusoidal waveform at a frequency of 10 Hz, stress ratios (where R = minimum stress/maximum stress) ranging from 0.1 - 0.9, and at ambient temperature. The test environments were laboratory air, vacuum ($2–4 \times 10^{-8}$ torr), and an aqueous 3.5% NaCl solution, in which the notch tip and crack of the specimen was immersed. The loading procedure was K-decreasing (load shedding) and K-increasing for fatigue crack growth rates (da/dN) below and above 2.54×10^{-5} mm/cycle (10^{-6} in./cycle), respectively. The crack length was continuously monitored with a computer system using a compliance measurement technique.

After the fatigue test, one side of the C(T) specimen was ground, polished, and etched in Keller's reagent to reveal the microstructure. With a metallograph , the resulting microstructure was also examined to identify the crack path.

Results and Discussion

Fatigue Crack Growth Rate

In both laboratory air and aqueous 3.5% NaCl solution, raising R increased the near-threshold fatigue crack growth rate and decreased the threshold stress intensity range ΔK_{th}. Typical examples are shown in Figs. 2 and 3. Similar behavior was reported for underaged, peak-aged, and overaged 7075 aluminum alloys tested in moist air of 95% relative humidity [1], 2024-T351 aluminum alloy in dry and wet argon [2], Al-3% Mg alloy in dry nitrogen at 298°K and in liquid nitrogen at 77°K [3], 7091 aluminum alloy in air of humidity greater than 90% [4], and 2024-T3 aluminum alloy in laboratory air at ambient temperature [5]. Such observations have also been made for low and medium carbon, medium carbon alloy, 2¼ Cr-1 Mo, rotor, 4340, JIS SB42, and AerMet 100 steels [6-15].

However, the reverse (a decrease of near-threshold fatigue crack growth rate and an increase of ΔK_{th} with increasing R) was observed in vacuum. Sample data of this result is shown in Fig. 4.

For a given R, the near-threshold fatigue crack growth rate at a given ΔK and ΔK_{th} was found to be the least and greatest in vacuum, respectively, intermediate in the aqueous 3.5% NaCl solution, and the greatest and least in laboratory air, respectively. Fig. 5 depicts an example of this fatigue crack growth behavior for the three testing environments at R = 0.7.

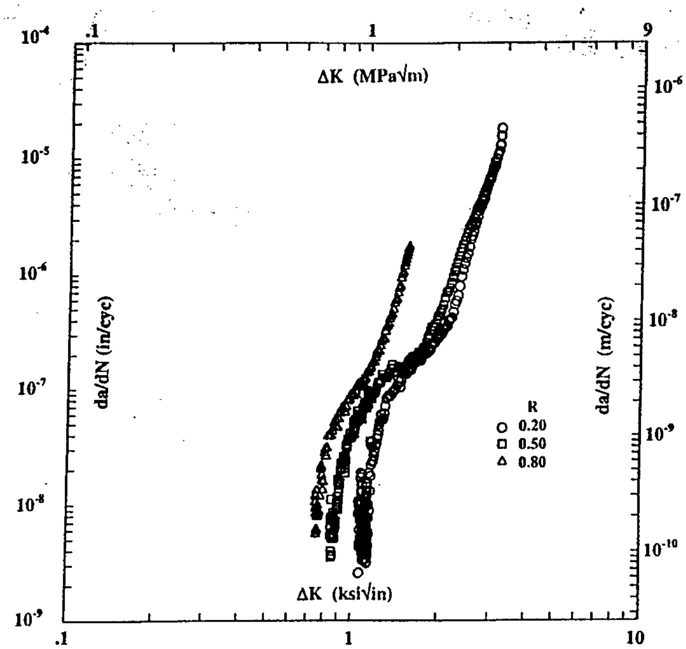


FIG. 2 – *Data showing variation of fatigue crack growth rate da/dN with stress intensity Range ΔK at stress ratios R = 0.2, 0.5, and 0.8 in laboratory air.*

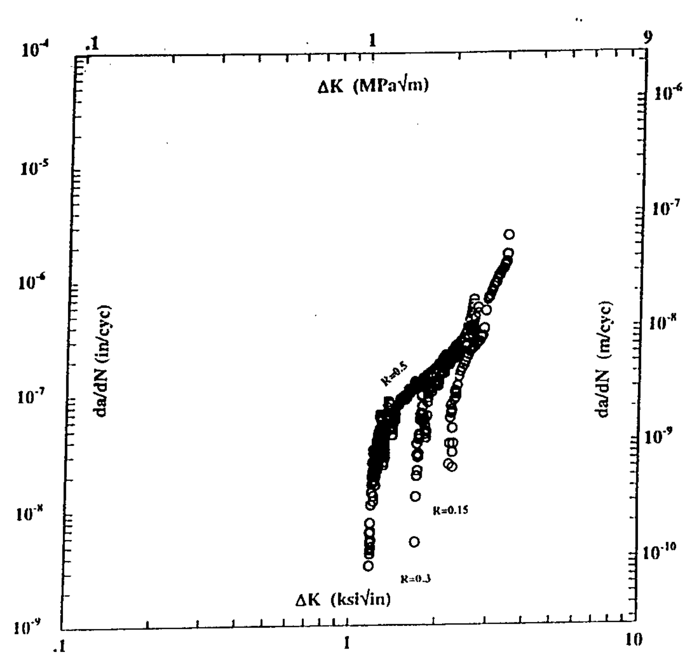


FIG. 3 – *Data showing variation of fatigue crack growth rate da/dN with stress intensity Range ΔK at stress ratios R = 0.15, 0.3, and 0.5 in an aqueous 3.5% NaCl solution.*

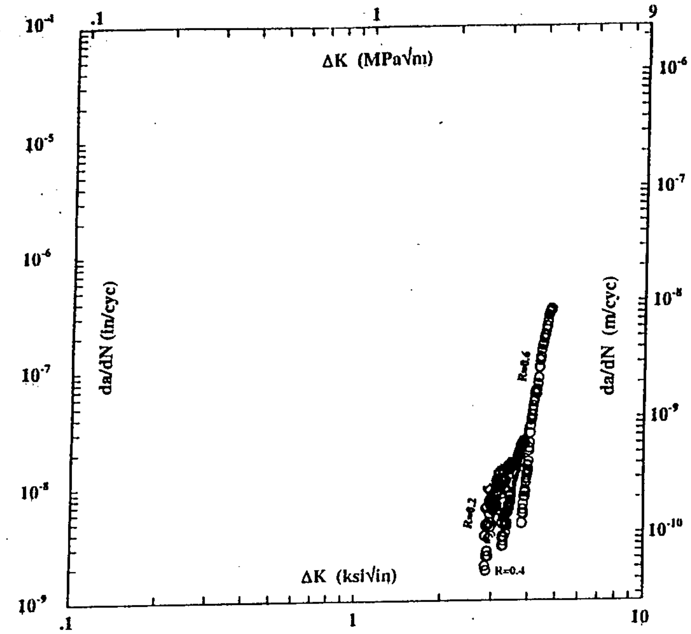


FIG. 4 – *Data showing variation of fatigue crack growth rate da/dN with stress intensity Range ΔK at stress ratios R = 0.2, 0.4, and 0.6 in vacuum.*

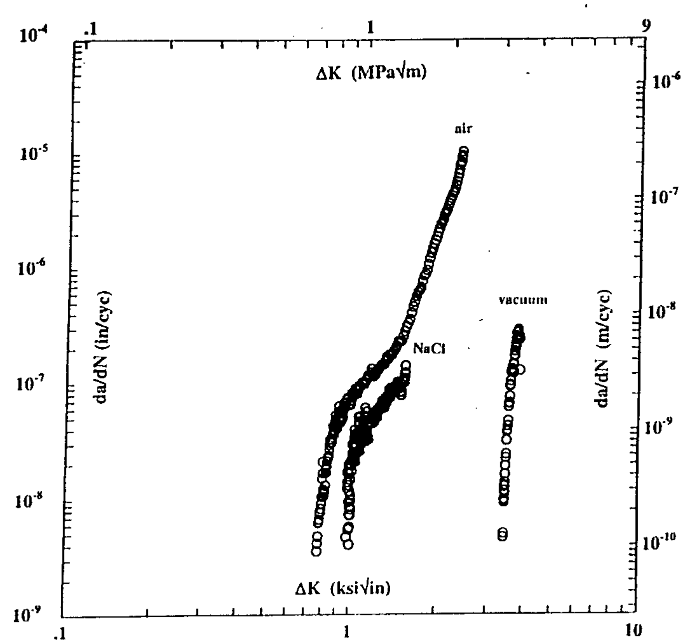


FIG. 5 – *Data showing variation of fatigue crack growth rate da/dN with stress intensity Range ΔK at a stress ratio R = 0.7 for testing in laboratory air, vacuum, and an aqueous solution of 3.5% NaCl solution.*

Threshold Stress Intensity Range ΔK_{th} and Maximum Stress Intensity K_{max}

From the aforementioned, ΔK_{th} varies with R and the environment, as does the corresponding maximum stress intensity K_{max} ($K_{max}=\Delta K_{th}/(1-R)$), which is a function of R. This variation with R is shown in Fig. 6 below.

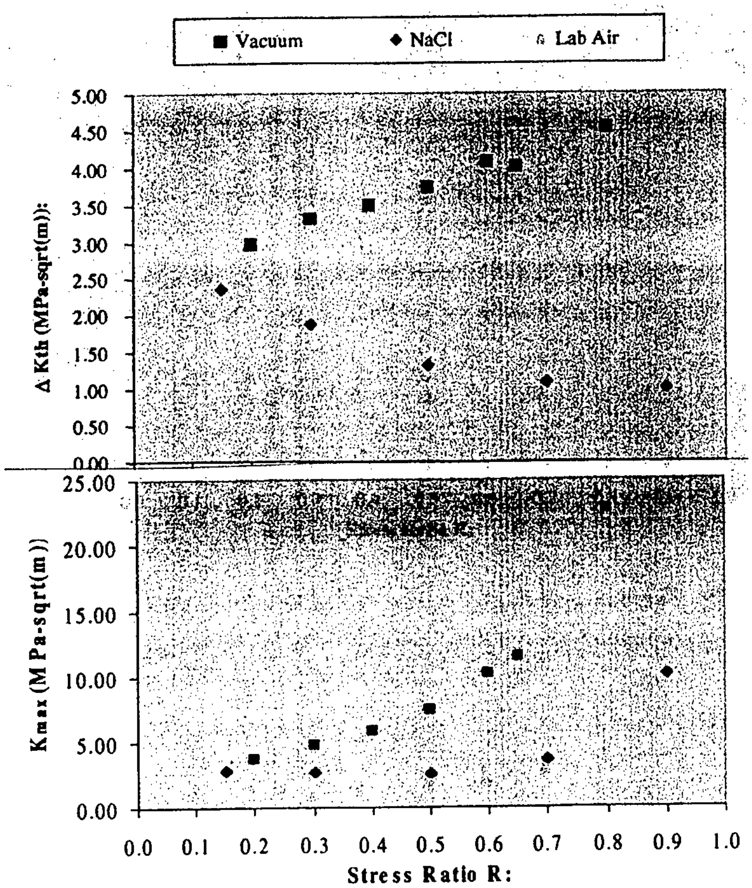


FIG. 6 – *Data showing variation of alternating and maximum stress intensities at threshold, ΔK_{th}, and K_{max} with stress ratio R in laboratory air, vacuum, and an aqueous solution of 3.5% NaCl solution.*

In both laboratory air and aqueous 3.5% NaCl solution, ΔK_{th} decreased with increasing R until a value of 0.5 was reached, and then leveled off or decreased slightly. Moreover, Fig. 6 shows these two curves converging at an approximate R = 0.9. The linear portion of the ΔK_{th} vs. R curve for R < 0.5 has a negative slope, and its extrapolation intersects the R-axis at $\Delta K_{th} < 0$ for laboratory air and $\Delta K_{th} > 0$ for aqueous 3.5% NaCl solution. The corresponding K_{max} initially increased slightly and then rose sharply. A similar observation has been reported for underaged, peak-aged, and overaged 7075 aluminum alloy in moist air of relative humidity 95% [1].

However, in a vacuum environment, with an increasing R, ΔK_{th} increased linearly, whereas K_{max} initially increased slightly and then rose sharply. For this case, the slope of the ΔK_{th} vs. R curve is positive, demonstrating a significant difference from the fatigue crack growth behavior in laboratory air and aqueous 3.5% NaCl solution.

Fig. 7 is a plot of ΔK_{th} against K_{max} for the fatigue tests in the three aforementioned environments. Such a plot, called a fundamental threshold curve [16], provides an interrelation between ΔK_{th} and K_{max} that define regimes where fatigue crack grows (above the curve) and where it does not (below the curve). Fig. 7 also indicates that the resistance to threshold fatigue crack growth is greatest in vacuum, intermediate in the aqueous 3.5% NaCl solution, and least in laboratory air for a given K_{max}.

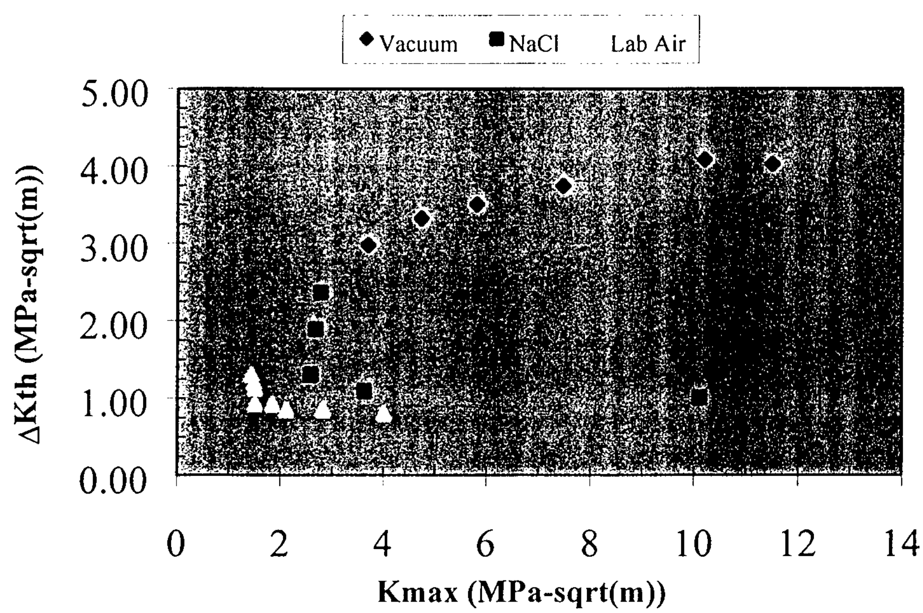
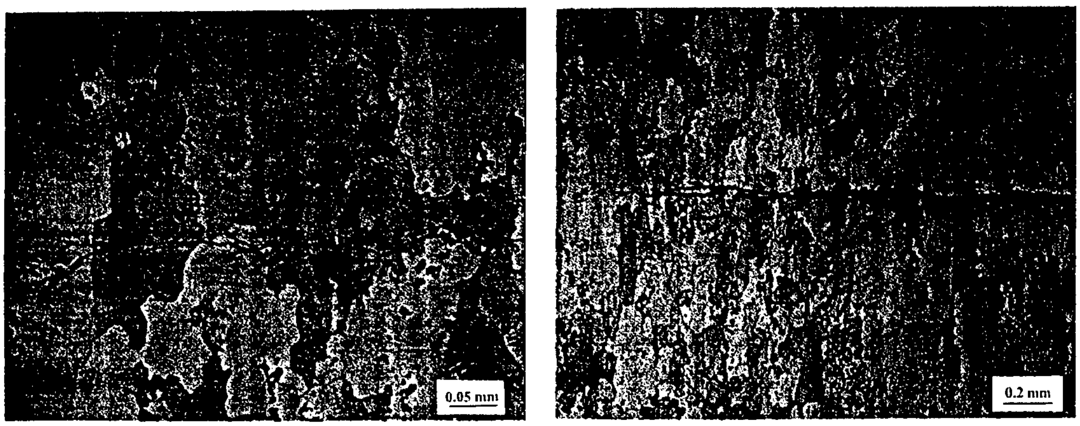


FIG. 7 – *Fundamental threshold curve, plot, showing variation of ΔK_{th} with K_{max} in laboratory air, vacuum, and an aqueous solution of 3.5% NaCl solution.*

The greater resistance to threshold fatigue crack growth observed in aqueous 3.5% NaCl solution than in laboratory air is attributed to crack closure, induced by corrosion product at the crack tip, as reported for steels [8, 10-13]. At a higher K_{max} or higher R, both of the fundamental threshold curves for fatigue testing in laboratory air and aqueous 3.5% NaCl solution converge, demonstrating a similar resistance to threshold fatigue crack growth in the two different environments. This must be associated with the diminishing of crack closure by corrosion product at the higher R-value in the aqueous 3.5% NaCl solution.

Crack Path

For samples fatigue tested in laboratory air and in an aqueous 3.5% NaCl solution, the crack path was observed to be mostly linear, transgranular, deflecting at grain boundaries, and with some branching. No significant difference was detected between the crack path morphologies for the differing stress ratios and environments. Representative crack path morphologies are shown in the following Fig. 8.



(a) *(b)*

FIG. 8 – *Micrographs showing crack paths in specimens tested in laboratory air (a) and in an aqueous 3.5% NaCl solution (b).*

Conclusions

1. Raising the stress ratio enhances the near-threshold fatigue crack growth with greater da/dN and smaller ΔK_{th} for specimens tested in laboratory air and in an aqueous 3.5% NaCl solution. However, the reverse is true for the vacuum environment.
2. The near-threshold fatigue crack growth is slowest with a smallest da/dN and greatest ΔK_{th} in a vacuum, intermediate with intermediate da/dN and ΔK_{th} values in an aqueous 3.5% NaCl solution, and fastest with the greatest da/dN and smallest ΔK_{th} in laboratory air.
3. In both laboratory air and aqueous 3.5% NaCl solution, ΔK_{th} decreases with increasing R until a value of 0.5 is reached, and then levels off or decreases slightly. The ΔK_{th} values for these two environments converge at a higher R-value. Conversely, in a vacuum, ΔK_{th} increases linearly with increasing R.
4. With increasing R, the threshold maximum stress intensity K_{max} slowly increases and subsequently rises sharply for all the three aforementioned environments.
5. The resistance to the threshold fatigue crack growth is greater in aqueous 3.5% NaCl solution than in laboratory air at a lower R. This is attributed to crack closure induced by corrosion product occurring at the crack tip.

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